

IMPACT OF ELECTRIC VEHICLE LOADS ON ELECTRIC POWER  
DISTRIBUTION SYSTEMS

By

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*In the Name of God, the Most Beneficent, the Most Merciful.*

All the praises and thanks be to God, the Cherisher and Sustainer of the Worlds.

The Most Beneficent, the Most Merciful.

The Only Master of the Day of Recompense.

You (Alone) we worship and You (Alone) we ask for help.

Guide us to the Straight Way.

The way of those on whom You have bestowed Your Grace and not of those who earned your anger, nor of those who went astray.

*Translation of Opening Chapter of the Holy Quran*

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## IMPACT OF ELECTRIC VEHICLE LOADS ON ELECTRIC POWER DISTRIBUTION SYSTEMS

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The voltages and currents on four distribution sites (FPL\_1 to FPL\_4) have been monitored. The load behavior with and without the EV load has been recorded. By performing laboratory tests on the GMC EV1 charger charging a fully discharged battery, the characteristics of the charger have been determined. The harmonic spectrum of the transformer current charging a fully discharged battery has been determined. The snapshots of the current and voltage waveforms have been recorded and studied. Based on the laboratory data a computer model of the charger and the distribution system has been developed. Comparing the simulation results to the laboratory results and the field data the simulation results have been validated. The simulated currents are roughly 4 to 10% away from the field recorded currents, in their magnitude and distortion. Based on the field data, laboratory results and the simulation results the derating of the distribution

transformer has been calculated. The two methods suggested for the calculation of derating have been presented and compared. The maximum and minimum limits of derating have been suggested. Using the first method the maximum derating is 20% and the minimum value is 99%. Using the modified method the derating remains close to 99 % throughout the charging cycle. (It must be noted here, that a derating to 20% means that the transformer can safely handle only 20% of its full rated load. Likewise a derating to 99% means that the transformer can handle 99% of its full rated capacity. Thus, a transformer derated to 20% is highly derated and a transformer derated to 99% is slightly derated.) After establishing the reliability of the simulation, by comparing the simulation results with the field data and laboratory results, a charging scenario with shorter charging times (45 minutes and 1.2 hours) has been simulated. The distribution transformer derating corresponding to these short-charging times has been calculated and presented. Furthermore, recommended scope for further research has been suggested which among other things, involves validating the derating formula for distribution transformers.

## CHAPTER I INTRODUCTION

### 1.1. Background

From the state of being a concept vehicle, a possible means of future transportation and a dream, the Electric Vehicle (EV) has become a reality. But even after the first major commercial launch of the EV1 by General Motor Corporation, the future of EVs is still under a cloud of uncertainty and some unanswered questions.

The popularity of EVs as a future mode of transport can be attributed partly to exhausting reserves of natural energy resources and environmental considerations. These and many other factors have boosted the research and development of the EV technology and a possibility of it being accepted as the popular mode of ground transport in the not so distant future. There has been a great boost to EV research because of government and industrial funding. This research has been mainly aimed at improving the battery technology, charging techniques, weight, comfort and reliability. For the environmentalist, the EVs' noiseless operation compliments its pollution free performance, and, for the customer, the EV is a good performance machine with the downside of short battery life, long recharging time and high initial cost.

The EV1 manufactured by General Motors Corporation is powered by a Delco Valve-Regulated Lead Acid battery pack, which contains 26 12-volt modules, capable of carrying 16.2-kilowatt hours of energy. The batteries can be recharged from 0 to a full

state of charge in approximately 3 hours using a 240-volt inductive Magne charge charger and about 15 hours from a 120-volt portable charger. Inductive charging is achieved without metal-to-metal contact. The alternating current powers a device that produces a fluctuating magnetic field in a paddle that is inserted into a port at the front of the car. This induces an alternating emf in a winding inside the car. This alternating emf is then rectified and fed into the batteries. The inductive charging system is inherently safe even under hazardous climatic conditions, since the windings are safely encased in a plastic cover. Typically this system can handle power levels from 1.5 to 25 kW with overall efficiency of 90% while the power transfer frequency is 40-350 kHz [1]. The specifications of the EV, as published by General Motors [PrEView Drive program literature], are summarized as follows:

1. 137 H.P. three-phase ac induction motor.
2. 16.8 kWh lead-acid battery.
3. Inductive coupled standard charger (220 volts, 30 Amps)
4. IGBT power inverter module.
5. Range: 90 miles highway, 70 miles EPA city.
6. Acceleration from 0 to 60 mph in 8.5 seconds.
7. Electronically regulated speed of 80 mph.
8. Charging time from 85% depth of discharge is 2 to 3 hours.
9. Curb weight is 2970 pounds.

While the popularity and widespread use of EVs on one hand will take ground transportation into a new era, on the other hand it can put additional and unprecedented strains on power supply and distribution systems.

For power systems, the EV loads pose twofold problems. These are:

1. Increase in power demand
2. Decrease in power quality.

The power distribution system looks at the EV as an additional load of about 7kw/EV (based on the GMC EV1), which was almost certainly not foreseen when most of the present distribution systems were designed more than a few decades ago. The fact that the EV charger load is a non-linear load with power electronic devices makes matters worse, for it is a source of harmonics and distortion in the distribution system. These harmonics which get injected into the system have a significant impact on the distribution system in terms of losses and overall performance of the power system. The non-linearities and harmonics caused by EV chargers can adversely affect other sensitive loads that may be connected to the distribution system. The power quality can become a major concern if the battery and charger technology is developed such as to put an extra strain on the distribution system. For example, research is now being aimed at developing batteries and their chargers which would make it possible to charge a completely exhausted battery in a very short period of time (15 minutes).

## 1.2. Project Justification

Existing distribution systems may not have the capability to cater to the new needs of customers if the use of EVs becomes widespread. The electric power utility companies need to be aware of and prepared to face such load scenarios. The utility companies need to first have a reliable assessment of the possible future load scenarios with EV loads. After this, they need to have a ready design of the new distribution system

equipment in terms of their sizes and ratings and also in terms of the configuration or the layout of the entire distribution system. Thus, in case of an increase in the use of EVs by the customers, the utilities will find themselves well prepared and thus continue to reliably supply quality power to their customers.

### 1.3. Objectives and Goals

The aim of this project is to provide Florida Power and Light Company with an assessment of the possible load effects with EV loads. The outline of the objectives of the project is given below.

- To study the normal load behavior for a typical distribution system feeding two to ten houses.
- To study the load behavior when one of the houses in the above case owns an Electric Vehicle.
- To perform laboratory tests to determine the behavior of the General Motor EV1 charger, in terms of its current requirements and harmonic effect on the input line.
- Based on the above data to prepare a computer model of the distribution system feeding loads consisting of EV loads.
- Prepare the mathematical model for various components and the whole system.
- Perform basic statistical analysis of the recorded data.
- Use computer simulations to study various possible load scenarios.

### 1.4. Major Contributions

Major contributions of this dissertation work are itemized below.

- Actual field data was recorded from distribution transformer sites. This data contains information about the load behavior and characteristics at these particular sites. It has been for the first time, that such data has been made available, for load scenario comparison between loads with and without the EV loads.
- Harmonic analysis has been performed on the field-recorded data, to identify the signature that the EV load leaves on the system. This has provided with an understanding of the EV load behavior when put on the system along with other domestic loads.
- Actual laboratory testing of the EV charger, charging into a fully discharged battery has been carried out. For the first time, GMEV1, charger has been tested when operated in isolation from any other external disturbance or interference. The testing procedure has been developed and applied to find the current, power, voltage, power factor and harmonic characteristics of the EV charger.
- Computer simulation of the distribution system feeding EV loads has been carried out. The simulation results have been compared with the actual field and laboratory results. Thus, establishing the accuracy of the simulation results.
- Fast charging time EV chargers have been simulated and their expected behavior has been studied. Although these chargers are not commercially available, however, these simulation results have provided a basis for understanding the expected behavior of such chargers once such a technology becomes available.
- Generalized load profile on a distribution transformer site has been developed.
- An IEEE/ANSI method for the calculation of the derating of transformer feeding non-sinusoidal loads has been modified. The proposed method yields more accurate and realistic results.

#### 1.4. Research Phases

The objectives of the thesis outlined in 1.3 have been achieved by dividing the whole research work into various phases. These phases are outlined as follows and later on in the section they are explained in more detail.

These phases are:

*PHASE I DATA PHASE:*

This phase consists of:

- The recording and analysis of the field load data with and without the EV being a part of the load.
- The laboratory testing of the characteristics of the EV charger.

*PHASE II MODELLING PHASE:*

This phase consists of:

- The physical model of the various components of the distribution system.

*PHASE III COMPUTER SIMULATION PHASE:*

This phase consists of:

- Computer simulation of the power distribution system and the analysis of simulation results.
- Create and study of different load scenarios with multiple EV loads.
- Create and study load scenarios with EV loads of variable charging times.

*PHASE IV. DESIGN PHASE:*

This phase consists of:

- Calculation of expected derating of a distribution system transformer based on the simulation results for:
  - Normal charging time chargers.
  - Short charging time chargers. (Quick Chargers)

## CHAPTER 2

### LITERATURE SURVEY

The issue of power quality is as old as the issue of electric power itself. But due to changing load conditions and customer needs, the importance and significance of supplying high quality power has changed with time. In the last decade, due to the increase in the use of power electronic equipment, power quality has attracted the attention of the utilities and customers alike. The utilities look to supply quality power to its customers at a price dependent on the amount of distortion that the customer is causing. The customers on the other hand want a reliable, sag free power to be delivered to them at a highly competitive price.

The study and research in the field of electric power quality can be traced to 60's [1] and 70's [2,3]. The fact though is that such studies were sparse. Power quality during that era was just a limit applied to fluctuations of frequency and voltage, to the voltage unbalance, voltage transients and flickers and power cuts [1,2]. Owing to the absence of vast amount of non-linear loads, power quality and harmonics was a factor more of an academic importance rather than a serious practical concern. The harmonics in the power systems were mostly caused due to load switching and telephone interference. During the 80's with the first power electronic revolution, the use of power electronic equipment was on an increase. Most of the power electronic loads are switching loads and are highly non-linear; these loads thus cause a

lot of harmonics to be injected into the system. This prompted the academia to study the power system harmonics in a greater detail, this included devising methods for the actual measurement of system harmonics, making case studies and estimating their effect on transformers, feeders and lines [4,5,6]. In the mid 80s [7] the increase in the presence of non-linear power electronic loads was obvious and a further increase was anticipated. This increase was owing to first the change in the technology e.g. faster and more efficient power electronic devices, better converter topologies and converter control methodologies, second the advent of fast microprocessors and their application to power electronic converter drives. The microprocessor controlled drives were more efficient and reliable, had the flexibility of speed control over a wide range, were easy to control and were compact in size. The need for technical understanding of the nature of electric disturbances caused by these non-linear loads was felt. Thus, in the face of changing load scenarios, there was a need for power quality education that included definitions, grounding practices, power line dynamics, case experience and trouble shooting [8]. In and after the late 80s a sharp increase in the published literature on power quality and harmonics can be found. The number of these publications is so large that it is impossible to list all of them, thus a selection of these papers has been listed here. Decrease in power quality that not too long ago was a mere speculation, was now viewed as a serious threat to the normal operation of power systems [10]. Research was thus directed towards development of harmonic mitigation techniques [11] as well as development of power electronic converters which would cause minimum harmonic distortion. Papers recommending different methods for the estimation and monitoring of power system harmonics were published [12,13,14]. References 15 – 25 include papers on the study and characterization of specific non-linear loads and their effect on power systems. The studied

loads consist of fluorescent lighting loads, electric drive loads, railroad loads and some other types of non-linear loads. In addition to these papers, scores of publications dealing with the study of the effect of harmonics on various power system equipment can be found in the literature [25 – 30].

The last few years have seen a phenomenal increase in the use of computers by the power customers. The computer loads, which are highly non-linear [31], although, exist significantly as commercial loads but the number of home computers is also increasing every day. [32]. Power quality is no longer an issue that is linked with just reliability, efficiency, voltage sags and flickers; today power quality is understood literally as the quality of the actual current and voltage waveforms. The power customer today has become very sensitive to the quality of power in terms of waveforms that the utility is providing. This sensitivity is owing to the changing needs of the customers, for instance in some cases the equipment powered from the line is highly sensitive to harmonics. Also, both commercial and domestic customers are more aware of harmonics and the impact they have on the performance of equipment and utility bill.

One of the very sources of harmonics in the power system is used to assess and remedy the situation. Computer modeling and simulations are being used for the study of various non-linear loads and the impact they have on power systems.[33-37]. In the midst of the talk and concern about increasing disturbance and harmonics, yet another type of non-linear load has appeared on the horizon. This is the electric vehicle load. The electric vehicle load has attracted the attention of the researchers and the utilities alike.

### CHAPTER 3

#### POWER QUALITY AND HARMONIC DISTORTION

Power quality, in simple words can be defined as the amount of distortion in the system current and/or voltage waveforms. The power systems and equipment are designed for pure sinusoidal current and voltage waveforms. Nowadays, widespread use of computers, florescent lights, Adjustable Speed Drives and many other power electronic equipment by customers cause a considerable amount of distortion of the voltage and current waveforms. The distortion is caused due to the inherently non-linear characteristics of these types of loads. In the presence of this increasing level of non-linear loads, the utility companies need to continue catering to the customer needs, which is supplying quality power with a high degree of reliability. This could necessitate new and stricter distortion guidelines for power customers, as well as a variable rate structure being developed. Also, utility engineers need to deal with the issue by analyzing the distortion and plan to control it by employing methods to either minimize the distortion by using some mitigation techniques or derate the existing system equipment to better cope with the steadily increasing non-linear load scenario. Electrical energy consumption in the United States in the year 1992 was of the order of  $600 \times 10^9$  kWh/year [38]. With the advances in power electronic converters, computers and many other non-linear loads, more and more of the proportion of this power would be used by such non-linear, distortion causing loads.

### 3.1. Harmonics

The non-linear characteristics of the loads cause the distortion of the current and/or voltage waveforms in a power system. These current and voltage waveforms are periodic in nature but they are not pure sinusoids. The distorted waveforms can be expressed in the form of a Fourier series. Using the Fourier series expansion, a distorted periodic wave can be expressed as the sum of an infinite number of sine waves, whose frequencies are an integral multiple of the fundamental frequency.

The distorted periodic waveform  $f(t)$  can be expressed as:

$$f(t) = a_0 + \sum_{n=1}^{\infty} [a_n \cos(n\omega t) + b_n \sin(n\omega t)]$$

Where:

$a_0$  is the dc offset of the waveform

$a_n$  is the amplitude of the cos term

$b_n$  is the amplitude of the sin term

$n$  is the order of the harmonic

To study the effect of the distorted voltage and current waveforms on the power system, the principle of superposition is used. This means that the effect of each constituent (harmonic) of the distorted wave is studied separately and then the overall effect is found by adding the effect of individual harmonics. The fundamental constituent of the distorted waveform has a frequency of 60 Hz, the second harmonic has a frequency of 120 Hz, the third 180 Hz, and so forth. The equipment used in the power system is designed for a supply frequency of 60 Hz i.e. the fundamental frequency. The other constituent waveforms (harmonics) certainly have an undesirable impact on the equipment and the overall power system and its performance.

### 3.2. Estimation of Harmonic Distortion

Before assessing the qualitative and quantitative effect of harmonics on the power system, some kind of estimate or quantitative expression of harmonic distortion needs to be defined. Three methods of estimating harmonic load content are practiced [41]. The Crest Factor and The Total Harmonic Distortion (THD) are the most common methods. The third method is the K-Factor method.

#### 3.2.1. Crest Factor

The Crest Factor gives a very simple estimate of the harmonic content of the waveform. It is defined as the ratio of the peak of the wave to its Root Mean Square (RMS) value. A perfect sine wave by definition will thus have a crest factor of 1.414.

$$\text{Crest Factor} = \frac{\text{Peak Value of the Waveform}}{\text{RMS Value of the Waveform}}$$

If the Crest Factor of the waveform (voltage or current) is other than 1.414, it indicates some kind of distortion in the wave. This technique has a limitation, it does not provide information about the constituent harmonic frequencies. Knowledge of the harmonic frequencies and their respective amplitudes is important to study the effect of wave distortion on the system.

### 3.2.2. Percentage Total Harmonic Distortion (THD)

Total Harmonic Distortion (THD) is defined as the ratio of the sum of the RMS values of the harmonics to the RMS value of the fundamental.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} (I_n)^2}}{I_1}$$

The above expression shows that THD provides with a measure of the distortion of a waveform. Like the Crest Factor, the THD is also limited in that it does not provide any information about the frequencies and amplitudes of individual harmonics. While computing the THD for a wave, the relative phases of the various harmonics are also not considered. Nevertheless both Crest Factor and the THD are very useful to establish the presence or absence of waveform distortion.

### 3.2.3. The K-Factor

The K-Factor while providing an estimate of distortion in a waveform takes into account the harmonic frequencies and amplitudes. This fact makes it the most accurate available method of estimation of non-linear load harmonics in a system. This is the method used for the calculation of derating of dry-type power distribution transformers [42]. Reference 4 proposes an expansion of the K-Factor method. The author [41] proposes to use the K-Factor as a weighted sum. Each type of load is considered separately and then all the K-Factors are combined to create a composite harmonic fingerprint.

The K-Factor is defined as:

$$K = \sum_{h=1}^{\infty} I_h (pu)^2 h^2$$

### 3.3. Transformer Derating

Power transformers and distribution transformers are designed for sinusoidal currents and voltages. Name plate ratings of transformers hold for purely sinusoidal supply and loads. If the current gets non-sinusoidal, for instance because of the use of switching power supplies, solid state inverters, converters, Adjustable Speed Drives etc., the indicated ratings of transformers no longer hold. A high harmonic content in the output current waveform effects the transformer ratings. Load harmonic currents add a disproportionate amount of additional transformer heating, particularly in the form of winding eddy current losses and stray losses which are supply frequency dependent. Several methods are currently used in the industry to assess the derating of transformers for a harmonic application. The most widely used method is IEEE/ANSI C57.110. The IEEE/ANSI method was developed for power transformers and does not specifically address other applications such as distribution and dry type transformers. On the other hand, the K factor method can be applied to only dry type transformers. In general, the application of the IEEE/ANSI method provides conservative results when applied to a distribution transformer. This standard outlines the following method for calculating the transformer harmonic capability.

### 3.3.1. Transformer Capability Equivalent Calculation.

In this method a per unit value of non-sinusoidal current is calculated which will result in load losses in the transformer just equal to the highest loss region for 60 Hz rated operation. The winding eddy current loss under rated conditions at the point of maximum loss density is 15% of the local  $I^2R$  losses. Taking the fundamental component of current as 1 per unit and taking the measured per unit values of the current harmonics up to the 11<sup>th</sup> harmonic the derating of a transformer is calculated.

The maximum loss density of the local  $I^2R$  losses is assumed as 15%. Solving Equation 8 in ANSI/IEEE C 57.110 for the permissible current.

Following the procedure in the standard:

$$I_{max} = \sqrt{\frac{1.15}{1 + \frac{\sum f_h^2 h^2}{\sum f_h^2} \times 0.15}}$$

Using the values shown in Table. 1. and obtaining the amplitude of each harmonic from Figure 4, the maximum permissible non-sinusoidal load current is given by:

$$I_{max} = \sqrt{\frac{1.15}{1 + \frac{113.089}{4.75} \times .15}} = 0.501$$

Hence the ratio of transformer rating with and without the harmonic loads = .501

Table. I Harmonic Content of the Sample Waveform

HARMONIC (H)	PER UNIT CURRENT ( $F_H$ )	$F_H^2$	$F_H^2 H^2$
1	1	1	1
2	.16	.0256	.102
3	1.3	1.69	15.21
4	.267	.0712	1.139
5	1	1	25
6	.101	.010	0.36
7	.68	.462	22.638
9	.54	.291	23.57
11	.447	.199	24.07

Total		4.75	113.089
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### 3.3.2. Effect of Current Harmonics on the Neutral Current.

The previous sections of this chapter discuss the effect of harmonics on the distribution transformer. However there is some more concern for harmonic loads on multi-grounded wye systems [43,44]. The current harmonics in a Y-Y distribution transformer cause a high neutral current and an elevated emf of the neutral.

In an ideal case when the loads on the transformer are balanced, the neutral current which is the vector sum of the three phase currents is zero.

If:

$$I_A = A \sin \omega t$$

$$I_B = A \sin(\omega t + 240^\circ)$$

$$I_C = A \sin(\omega t + 120^\circ)$$

where  $A$  is the amplitude  $I_A$ ,  $I_B$  and  $I_C$  are the currents in phase  $A$ ,  $B$  and  $C$  respectively

The neutral current is the vector sum of the three phase currents and is given by:

$$I_N = I_A + I_B + I_C$$

$$I_N = A \sin \omega t + A \sin(\omega t + 240^\circ) + A \sin(\omega t + 120^\circ)$$

$$\therefore I_N = 0$$

Now if the load current is rich in the third harmonic, the third harmonic component

with amplitude  $T$  can be written as:

$$I_A = T \sin(3\omega t)$$

$$I_B = T \sin(3\omega t + 240^\circ)$$

$$I_C = T \sin(3\omega t + 120^\circ)$$

And as before

$$I_N = I_A + I_B + I_C$$

$$I_N = T \sin(3\omega t) + T \sin(3\omega t + 240^\circ) + T \sin(3\omega t + 120^\circ)$$

$$\therefore I_N = 3T \sin(3\omega t)$$

The net neutral current because of all the other triplen harmonics will yield similar results. As reported by Mansoor et al. [44], in a power system, even with load diversity, there is very little cancellation of the third harmonic. These high neutral currents cause the following problem [45]:

1. The heavy neutral currents cause the over loading of feeder transformers. They can cause further distortion of the voltage because they push the transformer into saturation. The saturated transformer then becomes a source of harmonics.
2. When the neutral conductor carries harmonic currents, additional heat is generated and the current carrying capacity of the feeder is reduced.
3. The neutral conductor for transformers is generally sized same as the phase conductor, but due to the triplen harmonic currents the neutral conductor current can exceed its rated value thus overloading the neutral that can lead to equipment failure.
4. The balanced triplen currents flow as circulating currents in the transformer delta primary winding. As a result, more current flows in the winding of the transformer than is detected by the transformer primary circuit over current protection device. This can result in the overloading of the transformer.

These high neutral harmonic currents cause a voltage differential between the neutral and the ground since the ground wire at harmonic frequencies can cause significant neutral conductor voltage drop. This is known as Common Mode Noise Voltage.

## CHAPTER 4 FIELD DATA RECORDING, REPRESENTATION AND OBSERVATION.

### 4.1. Introduction.

The effect of the EV loads on the power distribution system would depend on a number of factors. Once the EVs become popular one of the factors that is going to be of significance, is the usage pattern of the EV by its users. The usage pattern would obviously vary from individual to individual, it would depend on the lifestyles and specific needs of the customer, e.g. nature of his job, weather conditions, age of the user, so on and so forth. To generalize the usage pattern and come up with an accurate generalized model is surely a nontrivial problem. Based on field-recorded data and knowledge of the EV load behavior, a typical load profile of a distribution node feeding EV loads can be constructed. Even though this load model won't be accurate but it will contain enough information to enable the utilities to design the distribution transformers, so that they are able to supply power reliably and economically. The usage pattern of users on the same distribution transformer shall determine the load diversity factor, the expected peak load on the transformer and the overall derating of the transformer.

The objective of the field data monitoring thus is threefold. First to get the load profile during two separate periods viz. when none of the customers are using an EV and when one of the customer is using an EV. Second to try and identify the signature or effect of the EV load when it is connected to the system. This effect is in terms of

increase in power demand and possible decrease in power quality. Lastly, this field recorded data can form the basis for configuring system computer model used for carrying out computer simulation study.

The objectives of field data monitoring have been achieved by monitoring the field data (system voltages, currents, power factor etc.) first for a period of time (two weeks) when the EV load is not a part of the loads on the distribution transformer. This is followed by a two-week period then when one of the customers is using the EV. The data obtained during the above two load scenarios has been analyzed. The comparison of these load scenarios has been used to establish a generalized load scenario when one of the customer on a distribution node is using an EV.

#### 4.2. General Considerations In Data Acquisition And Processing

Appropriate techniques for the acquisition and processing of random data are heavily dependent upon the physical phenomenon represented by the data and the desired engineering goals of the processing. In broad terms, however, the required operations may be divided into five primary categories as follows:

- a. Data collection
- b. Data recording (including transmission)
- c. Data preparation
- d. Data qualification
- e. Data analysis

Each of these categories involves a number of sequential steps. The purpose of this section is to summarize basic considerations associated with each of these key steps.

#### 4.2.1. Data Collection

The primary element in data collection is the instrumentation transducer. In general terms, a transducer is any device which translates power from one form to another. In an engineering context, this usually means the translation of some measure of a physical phenomenon of interest into an analog signal with a calibrated relationship between the input and output quantities. This translation may involve up to three basic operations; (a) a mechanical conversion of the physical quantity of interest into an intermediate mechanical quantity, (b) a pick off step which converts the intermediate mechanical quantity into an intermediate electrical quantity, and (c) an electrical conversion into a final electrical quantity, usually voltage. Some transducers may combine any two or all three of the operations, depending upon the physical quantity being measured and the specific nature of the transducer.

For example, a thermocouple, which is widely used as a temperature transducer, converts a difference in temperature directly to a difference in voltage without intermediate steps. On the other hand, a resistance thermometer, another commonly used temperature transducer, first converts temperature to a change in resistance, and then converts the resistance change to an electrical voltage change.

Ideally, the above operations would be accomplished without distortion or modification of the time history of the physical quantity being measured. In other words, if the input time history is  $x(t)$  and the output time history is  $y(t)$ , the perfect transducer would provide an analog output,  $y(t) = c x(t)$ , where  $c$  is a simple calibration constant. Unfortunately, this ideal situation is difficult to achieve in practice. Gain and phase modifications as well as distortion producing non-linearities are often inherent in the

transducer operations. This fact makes the transducer a potential source of error in any data acquisition and processing program.

#### 4.2.2. Data Recording

For some applications, it is possible to perform all desired data processing directly on the transducer signals in real time. For most applications, however, this is not practical and some form of storage (and perhaps remote transmission) of the transducer signals will be required. The most desirable and convenient type of data storage system is the magnetic recorder or a computer hard drive memory. Although other types of recorders could be used, the magnetic recorder has the advantage of being able to store large quantities of data, and to reproduce them in electrical form. The most desirable way to transmit data signals is through electrical lines or telephone lines. There are obvious situations where this is not feasible; for example, retrieving data from a spacecraft in earth orbit. For such cases, radio transmission (telemetry) of the transducer signals is usually required.

#### 4.2.3. Data Preparation

The next key phase in data acquisition and processing is the preparation of raw data for detailed analysis. The raw data are usually supplied from the recorder in the form of voltage time histories (or as direct analog signals from the transducers, if the data are being analyzed on-line). A number of operations are needed at this point to make the voltage time histories suitable for detailed analysis. The first of these operations is generally classified as data editing.

Data editing refers to those pre-analysis procedures which are designed to detect and eliminate spurious and/or degraded data signals which might have resulted from acquisition and recording problems such as excessive noise, signal dropout, loss of signal due to transducer malfunctions. Editing can often be accomplished through visual inspection of the data time history signals by a talented analyst. In more elaborate data acquisition and processing systems, a specific instrument for quick-look evaluation might be employed. Real-time spectrum analyzers are popular for this application. It should be noted that the data editing step is more critical for the case of digital processing than for analog processing. This is true because once the data have been converted to a digital format, it is often difficult to detect even the most obvious errors in the original signal.

For the case of analog data processing, data preparation beyond editing usually includes only conversion into engineering units (calibration).

#### 4.2.4. Data Qualification

The correct procedures for analyzing random data, as well as interpreting the analyzed results, are strongly influenced by certain basic characteristics which may or may not be exhibited by the data. The three most important of these basic characteristics are the stationarity of the data, the presence of periodicities in the data, and the normality of the data. Stationarity is of concern because the analysis procedures required for non-stationary data are generally more complicated than those which are appropriate for stationary data. Periodicities in the data should at least be identified to avoid erroneous interpretations of later results. The validity of an assumption that the data (excluding periodicities) have a Gaussian probability density function should be investigated since

the normality assumption is vital to many analytical applications for random data. Qualification of sampled data in terms of these basic characteristics is indicated as a separate operation to be performed prior to detailed data analysis. In practice, however, it is often accomplished as an integral part of the data analysis phase. Practical considerations and procedures for such qualification will now be discussed.

#### 4.2. Data Analysis

The procedures for analyzing the properties of random data may be divided logically into two categories: the procedure for analyzing individual sample records, and the procedure for analyzing a collection of sample records given the properties of the individual records. Applicable data analysis procedures for these two categories are now outlined.

##### *MEAN AND MEAN SQUARE VALUE ANALYSIS.*

The first step is a mean and mean square value (or variance) measurement. This step is almost universally performed for one or more of three sound reasons. First, since the mean and mean square values are the basic measures of central tendency and dispersion, their calculation is generally required for even the most rudimentary applications. Second, the calculation of short time averaged mean and mean square value estimates provides a basis for evaluating the stationarity of the data. Third, mean and mean square value estimates can be extracted from other descriptive properties (probability density plots, correlograms, and/or power spectra) which might be measured later. The comparison of directly measured mean and mean square values estimates to the corresponding estimates extracted from other

analyses provides an excellent method for checking the data analysis equipment or computer programs for correct operation.

#### *POWER SPECTRAL DENSITY ANALYSIS.*

Perhaps the most important single descriptive characteristic of stationary random data is the power spectral density function, which defines the frequency composition of the data. For constant parameter linear physical systems, the output power spectrum is equal to the input power spectrum multiplied by the square of the gain factor of the system. Thus power spectra measurements can yield information concerning the dynamic characteristics of the system. To be more general, the mean square value of the data in any frequency range of concern is determined by the area under the power spectrum bounded by the limits of that frequency range. Obviously, the measurement of power spectra data, will be valuable for many analysis objectives. Secondary applications include its use for the detection of periodicities and as an intermediate step in the calculation of autocorrelation functions.

#### *PROBABILITY DENSITY ANALYSIS.*

The last fundamental analysis included in the procedure is probability density analysis. Probability density analysis is often omitted from a data analysis procedure because of the tendency to assume that all random phenomena are normally distributed. In some cases, however, random data may deviate substantially from the Gaussian form. If such deviations are detected by a test for normality, then the probability density function of the data must be measured to establish the actual probabilistic characteristics of the data. Furthermore, a probability density function estimate is sometimes used as a basis for a normality test.

### 4.3. Field Data Monitoring

#### 4.3.1. Data Acquisition Methodology

The data was recorded in the form of one cycle snap shots of voltage, current and power factor. These waveforms were acquired once every one minute interval. The voltage and current waveforms at the distribution transformer output terminals were recorded and stored temporarily in the local hard drive of the data acquisition system. The stored data was then down loaded to a personal computer over a telephone line using modems. The distribution nodes under study were feeding typical domestic loads at 110 volts and EV loads at 220 volts. At each of these locations the distribution transformer has typical domestic loads of 2 to 10 homes. At each location one EV was provided to one of the customers for a period of two weeks. The customer was asked to put the EV to normal use. The data at each location was recorded during time intervals that can be classified into three states. The first state is the period (about two weeks) when there was no EV load. The second state is the period (about 2 weeks) when one of the houses on the distribution transformer was using an EV. The third state was again when there was no EV load. Thus the field data collected represents the load conditions before; during and after the EV load was connected to the system. Figure 4.1 shows the data acquisition system layout.

#### 4.3.2. Data Monitoring Instrument

The field data was recorded using several BMI models 8020 Plus PQNode™ data acquisition instruments. The BMI model 8020 Plus PQNode™ monitors power quality phenomena in electric power systems. It combines the capabilities of instruments that

monitor continuous quantities, (such as voltage level, load level, power factor, and harmonic distortion), with the capabilities of instruments that record disturbances (impulses, wave shape faults, swells and sags, outages, cold load pickups). Monitoring continuous quantities requires that the monitored signals be sampled at a regular basis, while monitoring disturbances requires that the signals be continuously sampled, and recorded only if the signals exceed specified values. The BMI 8020 Plus PQNode™ continuously samples up to four voltages and four current - three phases and neutral. The instrument periodically records waveforms, RMS levels, frequency and temperature so those trends can be calculated. The PQNode™ is designed to interface with a personal computer via telephone line, and is equipped with an internal modem for this purpose.

#### 4.3.3. Data Management

The data acquired by the BMI data acquisition system was stored by the BMI unit in the hard drive of the device in the form of ASCII files. Each set of data was stored as a 4 K file. The actual information is in only 1 kilobyte of the 4 K space. After downloading the data files to the personal computer in the Power Quality and Power Electronics Lab, at The University of Florida, the data needed to be stored safely with adequate backups and at the same time consuming optimum space. The data also needs to be easily restorable whenever needed for analysis purposes. Using data acquisition and data storing software, the data was archived in the computer hard drive. The archived data occupies only one fourth of the space since the files are crunched together. The data was also backed up on tape drives connected to the computer. In this way it was made certain that the precious data is not lost in the event of a hard drive failure. For the purpose of

analysis, only the required amount of data is restored and after it is processed it is deleted from the hard drive and a fresh batch of data to be analyzed and processed is restored from the archives.

For each batch of data the THD trend is plotted. Also plotted are the voltage and current trends for all the harmonics from the second through to the fiftieth harmonic component. In addition to the harmonic trends, steady state trends are also plotted; these are the real power, apparent power, RMS current and power factor trends for the two phases between which the EV charger is connected. Each of the trend waveforms is displayed one by one.

After examining the harmonic and steady state trends for the selected days, typical real time steady state voltage and current waveforms at certain instances of time were also plotted. It may be mentioned here that the BMI instrument acquires the distribution node data in the form of real time waveforms of voltages and currents. Using these waveforms which are acquired during every fixed period of time, the computer software uses them to create various harmonic and steady state trends.

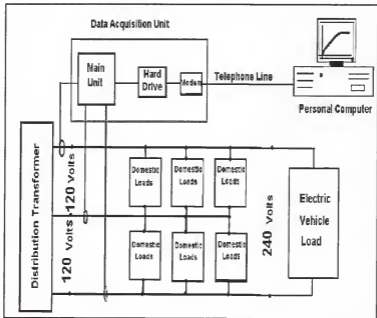


Figure 4.1. Data Acquisition System Layout

## CHAPTER 5 DATA REPRESENTATION AND ANALYSIS

### 5.1. Introduction

This section deals with the graphical representation of the recorded data. A visual inspection of the data trends is enough to show that the data represents stationary random process. It is assumed that all random phenomena are normally distributed. [data book] In some cases, however, random data may deviate substantially from Gaussian form. Looking at the data trends included in this chapter, the properties of the recorded data can be described at any instant of time by computing the average values over a collection of sample functions that define the random process. The stationary random data represented here falls in the category of ergodic random data. The properties of ergodic random process can be determined by performing time averages over a single sample function. Fortunately, in practice, random data representing stationary physical phenomena are generally ergodic. It is for this reason that the properties of stationary random phenomena can be measured properly, in most cases, from a single observed time history record.

The recorded data is presented in the form of various trends and waveforms. Each data trend for a particular site with and without the EV load are presented together to facilitate comparison between the two load scenarios namely when the EV load is the part of the load and when the EV is not a part of the load. The data recorded using the BMI data acquisition

units was synthesized using the software PASS<sup>TM</sup>. Broadly speaking two types of data trends were created and displayed graphically, viz. the steady state trends and the harmonic trends. For the purpose of studying the impact of Electric Vehicle loads on the distribution system, only the following trends have been selected:

1. The Steady State real power trend.
2. The Load Current Total Harmonic Distortion (THD) trend.
3. The various harmonic trends of the load current.

Although there are many other steady state and harmonic trends that were displayed using the PASS<sup>TM</sup> software, only the above mentioned three trends have been used for data analysis for the following reasons:

The EV charger load is a real power load, which consumes a peak power of 7 kilowatts (based on GM1 charger). The 7-kilowatt power is consumed when a fully discharged EV1 battery is connected to the charger. The power decreases as the charge on the battery increases. So one of the impressions that the EV charger load causes in the system is an increase in real power. Thus the real power trends for the distribution node with and without the EV load were created. This made it possible to compare the load scenario with and with out the EV load. From the laboratory testing of the EV charger, it was found that the EV load causes a distortion of the input line current. The General Motors EV1 is known to cause very little input voltage distortion [2].

The data represented in this chapter can be broadly classified into two categories viz.:

- I. When the distribution transformer is feeding normal domestic loads.
- II. When the distribution transformer is feeding normal domestic loads that also include Electric Vehicle Load.

Representing the data in this manner has facilitated the comparison of the load scenarios with and without the EV load.

## 5.2. Data Trends and Characteristics

Figure 5.1 through 5.7 are sample data trends created from the actual monitored field data. Each of these figures consist of two parts, viz. part a and part b. Parts a are the data trends without the EV loads, parts b are the data trends when the EV load is a part of the loads on the transformers. Following is the summary of highlights of each of the figures 5.1 to 5.7.

Figure 5.1: This figure represents the Total Harmonic Distortion trends of the line voltage. The voltage THDs for both cases are very close. Maximum voltage THD variation between “a” and “b” is 2%. The presence of EV loads does not have a significant effect on the input voltage THD. This fact is verified by the laboratory testing of the EV charger.

Figure 5.2: Unlike the voltage, the current THD trends shown in figure 5.2, are sensitive to EV loads. Comparing 5.2 a and 5.2 b, it can be seen that the current THD trend for two cases is not the same. When EV was a part of the domestic load, we see in 5.2 b, the current THD between the hours of 2:15 and 4:40 is very high. The current THD during this time varies between 80% to 40%. For the remaining part of the day, the current THD for both cases is close to each other.

Figure 5.3: These figures show the real power trends. The real power trend, when EV is a part of the load is not much different from the case, when EV is not a part of the load. This could be due to the fact that the customers do not fully discharge the batteries before

recharging them. Thus each time the battery charger load is put on the system, it draws only a fraction of its maximum rated power of 7 kilowatts.

Figure 5.4: These show the power factor trends. The EV load does not effect the power factor. Thus we see, in both parts of this figure the power factor trend stays close to .8.

Figure 5.5: These figures represent the third harmonic current trends. As in the case of the overall current THD trends, the third harmonic current trend between the hours of 2:15 and 4:00, show a high, for the case when EV is part of the load. The third harmonic component touches a high of 1.5 amperes during this period. This again indicates a possible presence of EV loads during these hours.

Figure 5.6 and 5.7: These are the fifth and the seventh harmonic current trends. The conclusions drawn from these trends are similar to those drawn from figure 5.5.

### 5.3. Data Observation

Observing the data trends represented in figures 5.1 through 5.7, the following conclusions can be drawn:

- I. The EV load does not have a distorting effect on the input line voltage. Thus the input line voltage THD is not effected by the presence of EV loads.
- II. The EV loads cause a considerable distortion of the line current. The line current THD is particularly high when the amplitude of the fundamental of the line current is small. Thus the current distortion is maximum close to the end of the charging cycle, when the charger draws a small current.

- III. The EV users generally would not be expected to fully discharge the batteries before recharging them. Thus the EV loads may not have a significant effect on the expected peak load on the distribution transformers.
- IV. The EV battery charger operates at a high power factor. Thus the reactive power drawn by the charger is low.
- V. The EV charger injects a significant amount of lower odd current harmonics into the power line.

#### 5.4. Load Characteristics

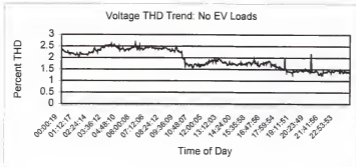
This section contains the computed maximum and the average daily power output of the distribution transformer. The daily average power is the average of the load over a period of two weeks. The load average has been found, first for the period (2weeks) when EV was not a part of the loads and next for the period of 2 weeks, when EV was a part of the load. Also, for these two two-week periods the maximum load profile has been computed. The figure X.8 a, has been derived by computing the load average for a 2-week period when EV was not a part of the loads. The figure 5.9b is the 2-week load average when EV was a part of the loads. Comparing, 5.8a and 5.8b, we see that there is an increase in the average power consumed, when the loads contain the EV load. This increase is particularly visible, during the early morning hours, this reinforces the previous conclusion about the times at which the EV load was connected to the system.

Figure 5.9 a and b, show the maximum power recorded during the two two-week periods. Plot in figure 5.9a is the maxima of the daily load curves of the two weeks period when EV was not a part of the loads. Plot 5.9b is the maxima of the daily load curves of the

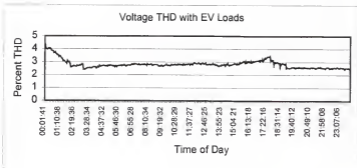
two-week period when EV was a part of the loads. It must be noted, the EV loads although do not effect the peak loads, nevertheless being an additional load it does affect the average daily power consumed.

Figures 5.10 a and 5.10 b, show the snap shots of the recorded line current waveforms. The line current snap shot of figure 5.10a was recorded when EV was not expected to be a part of the loads and 5.11a was recorded, when EV was expected to be a part of the loads. From the Fast Fourier Transforms (FFTs) of waveforms in figure 5.10a, shown in figure 5.10b, we see that the line current does not have a high content of the lower odd harmonics (viz. 3<sup>rd</sup>, 5<sup>th</sup> and the 7<sup>th</sup>). This is not the case with figure 5.11b, where these harmonics are significant.

Based on the preceding discussion, the load profile of Figure 5.9, qualifies for a generalized load profile of loads on a distribution transformer, for that particular site.

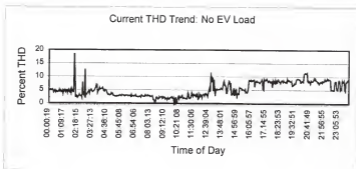


(a)

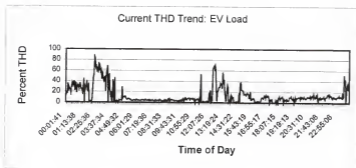


(b)

Figure 5.1 Voltage Total Harmonic Distortion Trends

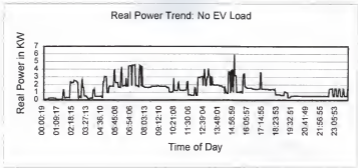


(a)

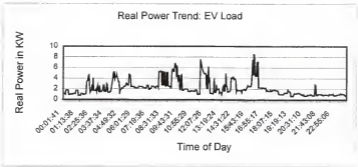


(b)

Figure 5.2. Line Current Total Harmonic Distortion Trends

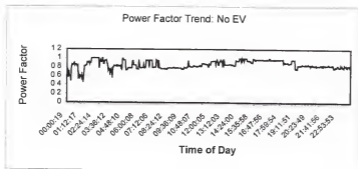


(a)

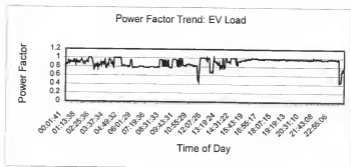


(b)

Figure 5.3. Real Power Trends

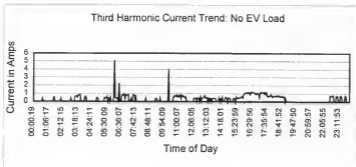


(a)

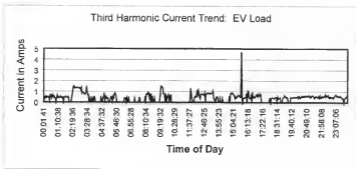


(b)

Figure 5.4. Power Factor Trends

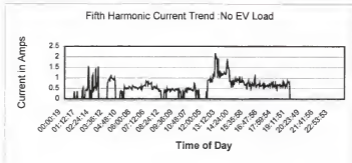


(a)

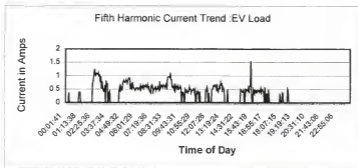


(b)

Figure 5.5. Third Harmonic Current Trends

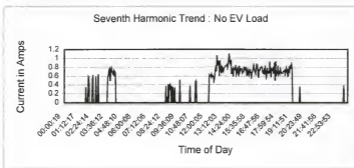


(a)

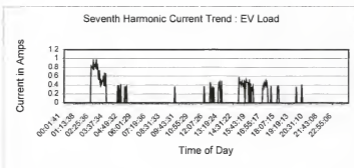


(b)

Figure 5.6. Fifth Harmonic Current Trends

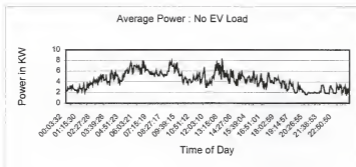


(a)

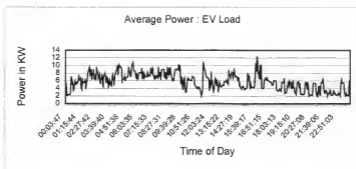


(b)

Figure 5.7. Seventh Harmonic Current Trend

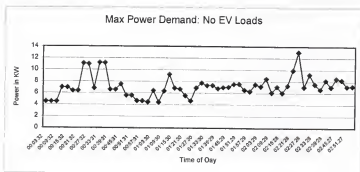


(a)

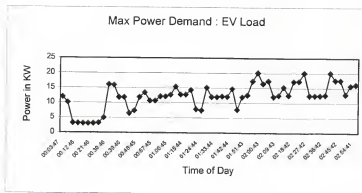


(b)

Figure 5.8. Average Power Computed on the Basis of Two Week Daily Load

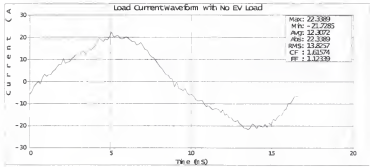


(a)

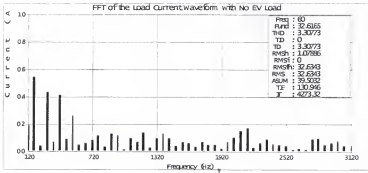


(b)

Figure 5.9. Maximum Power Demand Computed over Two Week Period

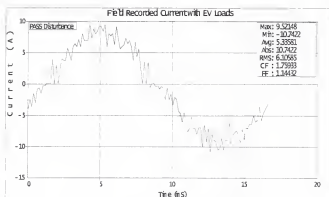


(a)

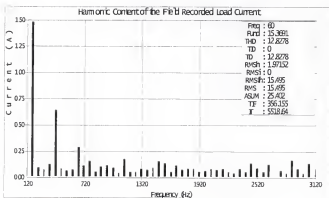


(b)

Figure 5.10. a) Line Current Waveform Snap Shot with No EV Load  
b) Fast Fourier Transform of the Current Waveform of "a"



(a)



(b)

Figure 5.11.

a.) Field Recorded Current Waveform.

b.) FFT of the Field Recorded Waveform in Figure a.

## CHAPTER 6

### LABORATORY TESTING OF THE EV CHARGER

#### 6.1. Testing Procedure and Results

The EV1 charger is a 240 volt split single-phase device. In the laboratory testing of the charger, a nearly fully discharged (5% of full charge) battery was connected to the charger. The voltages and currents on both input lines were measured; the equipment set up for the laboratory testing is shown in figure 6.1. Electrical measurements were taken using the power monitor, automatically once every one-minute interval for the entire charging cycle. The fully discharged battery was connected to the charger at 10:17 AM. The battery reached its almost full charge at 2 PM, a charging time of a little less than 3 hours. The EV1 charger when charging a fully discharged battery draws a current of 30 amps at 240 volts and is also a source of significant harmonics as shown in the following laboratory results. These results have been presented in the form of waveforms and graphs that depict the electrical characteristics of the EV1 charger.

The first graph, Figure 6.2 shows the power consumed by the EV1 charger over the entire charging cycle. The load varied from the maximum of 7kw at the beginning of the cycle to about 1kw when the battery is nearly completely charged. During the entire charging cycle the input voltage remained unaffected as far as either the magnitude or the harmonic distortion is concerned (Figure 6.3).

The input current however varied significantly in percentage harmonic content. Figures 6.4, 6.5, 6.6 and 6.7 show the current waveforms recorded at specified instants of time. It can be observed that as the amplitude of the current decreases the waveform distortion becomes more and more visible. Figure 6.9 shows the RMS values and figure 5.10 the Total Harmonic Distortion (THD) of the input currents for phases a and b, over the entire charging cycle. The figure 6.11 shows the harmonic content of the input current. It was seen that the amplitude of various harmonics throughout the charging cycle does not vary significantly. Since the amplitude of the fundamental component decreases with time and the THD, which is a percent measure of harmonics to the fundamental shows a significant increase with time.

## 6.2. Observation of Laboratory Results

The EV charger charging into a fully discharged battery draws a line current of 30 Amps at 240 Volts. This corresponds to a power consumption of approximately 7 kW at time 10:17 as shown in Figure 6.2. The voltage waveform as shown in Figure 6.3., stays distortion free throughout the charging cycle. The input line current distortion at the beginning of the charging cycle is less visible (Figure 6.4). This is because the amplitude of the line current is high and its THD which is expressed as a percent of the fundamental RMS current, is low. Note that in Figure 6.10 the THD at time 10:18 is just about 2 % for both line currents  $I_a$  and  $I_b$ . As the charge on the battery increases and the amplitude of the line current decreases, the current distortion becomes more and more visible (Figure 6.5 to 6.8). This is verified by Figure 6.10 where in at the end of the charging cycle, the THD of the line current climbs to almost 30 %. Although the THD of the line current increases as the charge on the battery increases, the actual harmonic content of the line current stays fairly constant. Figure 6.11

shows the line current harmonic content up to the 50<sup>th</sup> harmonic. The most significant harmonics are the 3<sup>rd</sup>, 5<sup>th</sup> and the 7<sup>th</sup>. The even harmonics are almost not present.

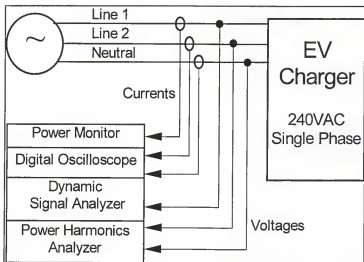


Figure 6.1. Experimental Setup for EV Charger Testing

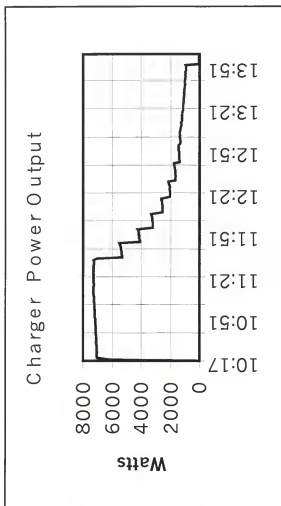


Figure 6.2. Power Curve for the EV1 Charger.

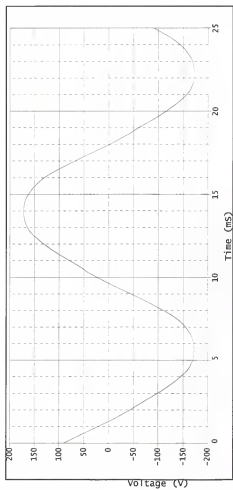


Figure 6.3. Typical Charger Output Voltage Waveform

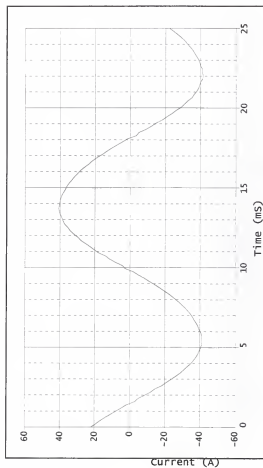


Figure 6.4. Charger Input Current Waveform Sampled at 11:19

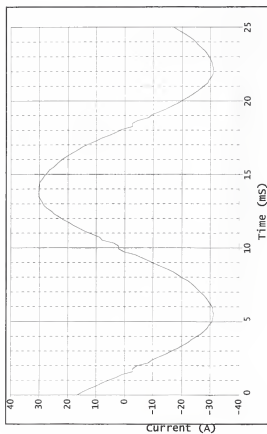


Figure 6.5. Charger Input Current Waveform Sampled at 11:40

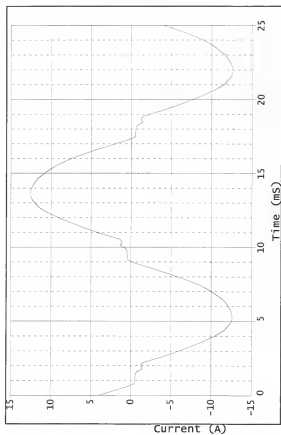


Figure 6.6. Charger Input Current Waveform Sampled at 12:07

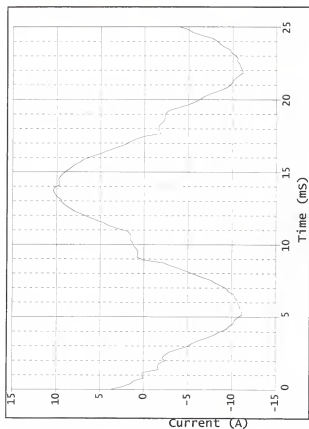


Figure 6.7. Charger Input Current Waveform Sampled at 12:36

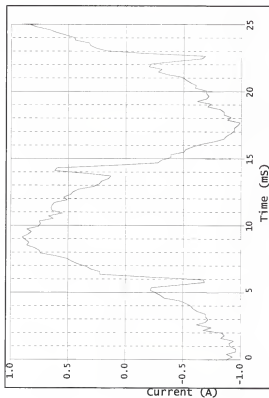


Figure 6.8. Charger Input Current Waveform Sampled at 13:53

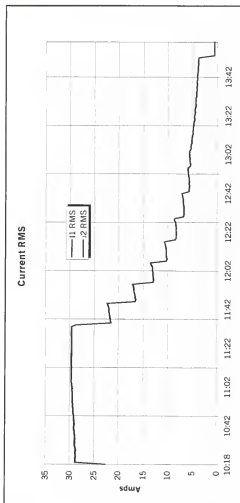


Figure 6.9. The Charger Current RMS Variation over the Charging Cycle

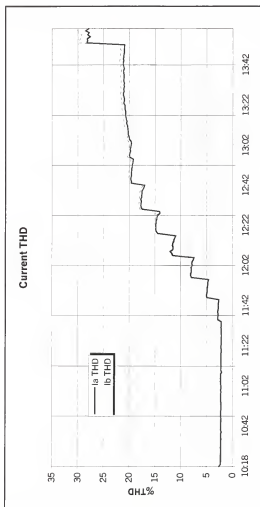


Figure 6.10. The Charger Current THD Variation Over the Charging Cycle.

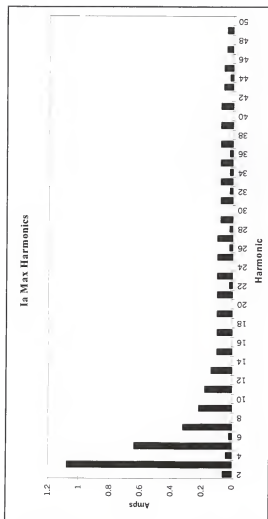


Figure 6.11. The Charger Input Current FFT.

## CHAPTER 7

### COMPUTER SIMULATION

This section contains the results of computer simulations of the power distribution system with domestic and Electric Vehicle (EV) loads. The domestic load included in these simulations is arbitrary. The EV model used is based on the laboratory data obtained by testing the actual charging characteristics of an EV charger used by the GMC EV1. The aim of this simulation is to see the effect of EVs connected to the distribution system. The transformer current with EVs present in the system is simulated. The FFT of the transformer current with and without EVs are shown and different harmonic components are found to study the effect of these harmonics on the distribution transformer in terms of the derating of transformers.

The power distribution system with an EV charger load was simulated using SABER™. This section includes the simulation results and discussion about the simulation model.

#### 7.1. Component Models

##### 7.1.1. System Model

The system model consists of the distribution transformer, domestic load and the EV charger and battery load. Figure 7.1 shows the layout of the simulated power distribution system. The distribution transformer has typical domestic loads connected at

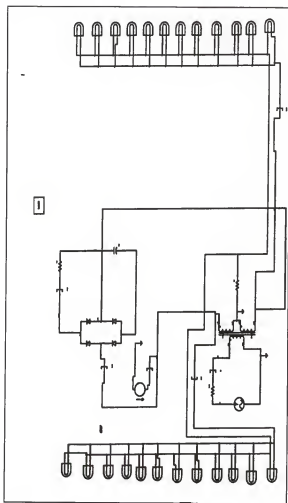


Figure 7.1. Distribution System Model.

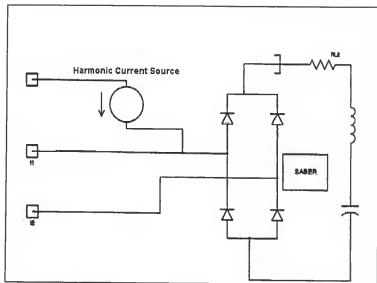


Figure 7.2. Simplified Model of the Simulated EV Charger

120 volts between the center tap and the outer terminals. The outer terminals, which are at 240 volts, are connected to a full bridge rectifier. The bridge rectifier is used to model the inductive charger used by the EV1 to charge its batteries.

### 7.1.2. Electric Vehicle Charger And Battery Models

The EV charger is modeled on the basis of laboratory data obtained during the charging of a fully discharged EV battery connected to charger. The full bridge rectifier represents the charger. The input to the rectifier is 240 V from the distribution transformer. The EV charger and battery model is shown in figure 7.2. The battery has been modeled as a series combination of a resistor and a capacitor. The resistance represents the loss component of the battery. It is presumed that the charging pattern of the capacitor shall closely represent the charging pattern of the EV battery. The values of the resistor and the capacitor can thus be chosen to achieve the desired charging current and charging time. In the simulation while the full wave bridge rectifier represents the EV load, a composite current source has been used to represent the harmonic effect of the EV charger. The composite current source is injecting harmonics of the same amplitudes and respective orders as shown in figure 3.2. The actual waveform of the harmonic current injected by the composite current source is shown in Figure 7.3.

### 7.1.3. Transformer Model

The transformer used for the simulation is a gap less three winding transformer with one primary and two secondary windings. The transformer in the simulation has the following specifications.

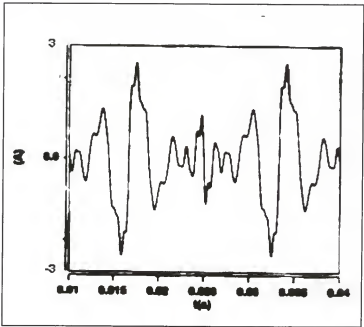


Figure 7.3. The Harmonic Current Injected by the Charger

These specifications were provided by FPL.

KVA RATING	37
Turns Ratio	7260, 120/240
Material of the Core	Grain oriented silicon steel
Thickness of Lamination	.009 inches
Net cross sectional area of the core	28.9 sq. inches
Path length	25.74 inches
Magnetization Saturation	20.0 Kilogauss

#### 7.1.4. Domestic Load Model

The domestic load has been modeled as a combination of some lighting and heating load represented by resistive load. The load has been modeled such as to exhibit the characteristics similar to the actual load characteristics as determined from the field data. Figure 7.4 shows a typical domestic load model used in simulation.

#### 7.2. Mathematical Model Of The EV Charger.

The EV charger can be represented by a single-phase bridge rectifier with an R-C load, as shown in figure 7.1 can represent the EV charger. A current source model is used for the injected harmonics when there is very little voltage distortion [9]. Since the EV charger is

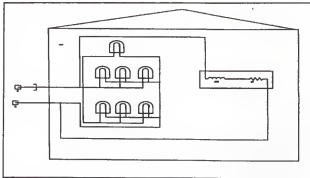


Figure 7.4. Domestic Loads Model

known to cause very little voltage distortion, the harmonics injected by the charger into the line can be modeled by a composite current source. The behavior of the charger can thus be determined by a second order system.

$$LC \frac{d^2 v_c}{dt^2} + RC \frac{dv_c}{dt} + v_c = v_s \quad (1)$$

where

$v_s$  — the transformer secondary voltage

$v_c$  — the capacitor voltage

$L$  — the equivalent battery inductance

$C$  — the equivalent battery capacitance

$R$  — the equivalent battery internal resistance

The net harmonic current from the composite current source can be expressed as:

$$i_H = \sum_{k=2}^{50} I_{mk} \sin k\omega t \quad (2)$$

where  $i_H$  is the net harmonic current

$k$  is the order of the harmonic

$I_{mk}$  is the amplitude of the  $k$  th harmonic current

The SABER™ software package was used to simulate the system, both transient and steady state operating conditions, including RMS values, THD etc can be obtained using SABER™. In the battery model the  $L$  is small and hence can be neglected.

Therefore the charging time constant ( $T$ ) for the battery can be given by:

$$T = RC \quad (3)$$

### 7.3. Simulation Results

In the computer simulation two types of loads have been considered, viz. the lighting loads and the EV load. The simulation results with two houses and a single EV load are presented. The lighting load current is taken as a pure sinusoidal current. The current harmonics injected into the mains by the EV charger are shown in figure 7.3. This is based on the experimental results obtained by testing the EV1 charger in the laboratory. The harmonic components of the charger input currents (figure 7.5) are supplied by the composite current source. The charger input current in the simulation is

controlled by varying  $R$ . We know from the lab test data that the maximum current that the charger draws (for fully discharged battery) is approximately 30 Amps.

By modeling the GM EV1 charger as a combination of a full wave bridge rectifier with a resistive and inductive load and a composite current source, simulation results very close to the lab results were obtained. A detailed discussion on the comparison of the laboratory results, the simulation results and the field-recorded data has been included in Chapter 7.

The simulation runs of the distribution system made it possible to check the various load scenarios in the distribution system. The system design can now be checked for an arbitrary number of EVs connected to it. This data obtained from simulations is important and makes it possible to optimally design/redesign future distribution systems. This includes replacing and/or adding transformer units in the existing systems in order to make them able to withstand the new load conditions caused by the EV load and the harmonic distortion associated with it.

Based on the field and laboratory data the EV charger has been successfully modeled. The simulation results are close to the laboratory results obtained during the actual charging of the EV battery. The waveforms on the input side of the transformer have a low order current harmonics.

#### 7.4. Simulation of Short Charging Time Chargers

The computer simulations were used to check scenarios when the charging time for charging the battery is much shorter. The GM EV1 charger takes about three and a half hours to charge a fully discharged battery (from about 15% of full charge). The long

charging time is a drawback with the EV and research is being done to reduce this charging time substantially. The fast charging time chargers are not commercially available and their behavior in terms of harmonic effect is not known. The computer simulations have been used to provide an estimate of the effect of the fast charging EV on the distribution system. The results of these simulations are based on the researcher intuition and experience of working with highly non-linear loads. The fast charger study is aimed at providing an idea about how such a technology, when developed can effect the distribution system. These results need to be verified once the fast charging technology becomes available.

#### 7.4.1. Simulation Methodology For Fast Chargers

The charger model for the fast charging charger is essentially the same as that for the normal charging time charger. The difference however is only in the values of the resistor and the capacitor that represents the battery. Also the amplitude of the harmonic currents has been increased proportional to the decrease in the charging time. Thus the fast charging time charger has also been simulated as a combination of a full-wave bridge rectifier and a harmonic current injection source. As mentioned earlier, these simulation results are based on intuition and experience of working with non-linear loads. These results can only be verified once fast charging technology becomes available. Figures 7.6 through 7.8 show the current waveforms and their respective FFTs for simulated scenarios where the charging time is reduced as indicated in the figures. The distribution transformer derating corresponding to this charging scenario is shown in Section 8.2.

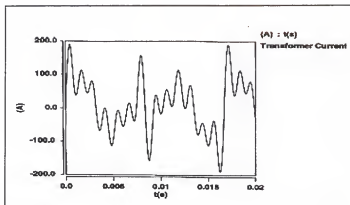


Figure 7.5 Transformer Current for the Fast Charging Charger with Charging Time of 45 minutes.

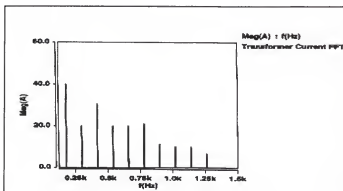


Figure 7.6 FFT of the Transformer Current for the Fast Charging Charger with Charging Time of 45 minutes.

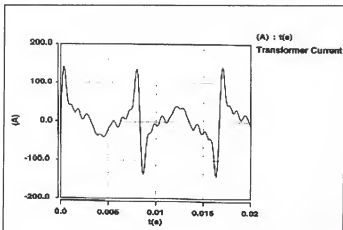


Figure 7.7. Transformer Current for the Fast Charging Charger with Charging Time of 1.2 Hours.

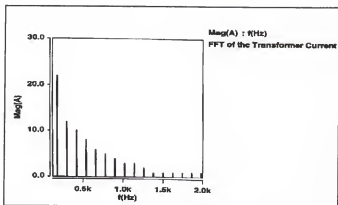


Figure 7.8. FFT of the Transformer Current for the Fast Charging Charger with Charging Time of 1.2 hours.

## CHAPTER 8

### COMPARISON OF FIELD, LABORATORY AND SIMULATION RESULTS

In this section, the field data and laboratory test results are compared with those done by computer simulation to present the effect of EV loads on the power distribution transformer.

The aim of this project is to study the impact of the EV load on the power distribution system. In summary, this goal has been accomplished by recording the field data with and without the EV load, recording the behavior of the EV charger by the laboratory testing of the GMEV1 charger charging a fully exhausted battery. The data acquired from the field provides the information about the characteristics of the distribution loads when EV load is a part of the load and when there is no EV load. The laboratory testing of the charger provides the input current characteristics of the charger and the line current harmonic content of the charger.

Using the data from the laboratory test, the computer simulation model of the EV charger has been built. The details of the computer model have been discussed in Section 8.1. Thus the laboratory testing of the charger forms the basis on which the computer model is built. The charger computer model has been incorporated into the overall model of the distribution system. The distribution system consists of the transformers, feeders, different types of normal domestic loads and the EV loads.

First of all, in this section, the accuracy of the computer model of the EV charger will be established. This has been achieved by comparing the laboratory test results of the

EV charger with the computer simulation results. Second, the similarity of the field-recorded data with the simulation results will be discussed.

### 8.1. The Field Data

The field data was recorded in the form of one-cycle snapshots of current and voltage as well as power factor at the distribution transformers at four different locations in South Florida and then transmitted to a computer over the telephone line. The detailed description about the data monitoring and acquiring methodology are mentioned in Section 4.2.

### 8.2. Laboratory Test

For the laboratory test the EV charger is selected as a 240 volt, split single-phase device as described in the previous section. The voltage and current input into the charger were monitored and recorded over the full charging cycle for the EV, which was nearly completely discharged to a level of 5% of full charge. Electrical measurements were taken using a power monitor automatically every minute over the entire charging period of about three hours.

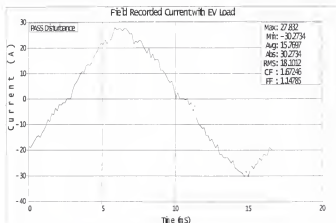
From the measurement it was found that the current supplied to the EV charger varies throughout the charging cycle. The charger current variation is shown in Figure 5.9. The actual amplitude of each of the harmonics in the charger current does not vary significantly during the charging cycle.

### 8.3. Simulation Results

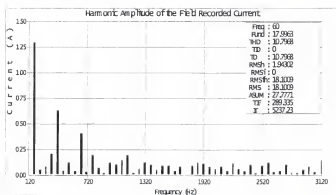
The power distribution system consisting of the feeder, distribution transformer, the EV charger, together with domestic loads (mainly the lighting lamps) was simulated using SABER<sup>TM</sup>. The models of various components used for simulation are based on both field data recorded and the laboratory data. To simulate variation of input current and distortion at different instants over its charging period, an adjustable resistor, as well as a composite current source which is based on the FFT analysis of the laboratory test data, is introduced in the loop. By varying the resistance, the identical situations to those in the laboratory test can be established. Therefore, current waveform snapshots over a whole cycle of 60 Hz are obtained and then compared with those recorded in the laboratory test.

### 8.4. Comparison

The field data, laboratory test data and simulation results are compared in terms of the waveform snapshots with the same magnitude of charger input current for all three cases viz. the field data, the laboratory test data and the simulation results. The aim is to establish the reliability of the laboratory test data; the simulation model and simulation results by comparing them to each other and the field recorded data. Some of the waveforms that have been included in previous chapters have been put in this section for convenience of comparison.



(a)

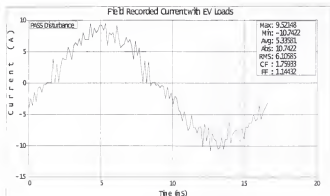


(b)

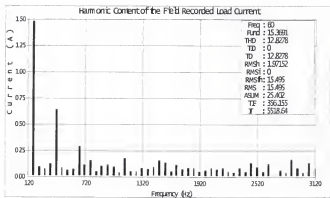
Figure 8.1.

a.) Field Recorded Current

b.) Waveform FFT of the Field Recorded Waveform.



(a)



(b)

Figure 8.2.

a.) Field Recorded Current Waveform.

b.) FFT of the Field Recorded Waveform in Figure 8.3.

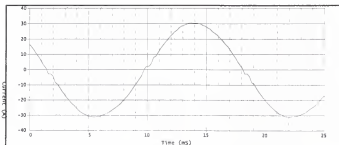


Figure 8.3. Laboratory Test Transformer Current at 11:40 AM

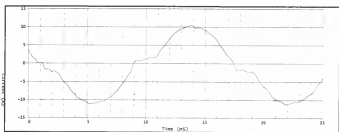


Figure 8.4. Laboratory Test Transformer Current at 12:36 PM

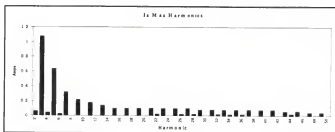


Figure 8.5. FFT of the Current Waveform of Figure 8.6.

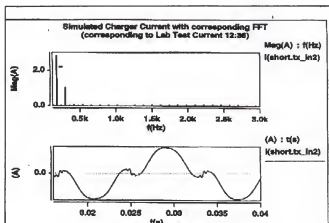


Figure 8.6. The Simulated Current Waveform and the Corresponding FFT

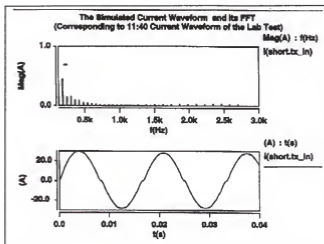


Figure 8.7. The Simulated Current Waveform and the Corresponding FFT

The waveform of figure 8.1 shows the field recorded current for the distribution transformer feeding two homes (FPL\_1). This is the distribution transformer current when the load on the transformer contains EV load. Figure 8.2 is the FFT of the waveform in Figure 8.1. The observation after comparing the current waveform of Figure 8.1 and its FFT in figure 8.2 with the laboratory recorded waveform in Figure 8.5 and its corresponding FFT in Figure 8.6 are presented in a tabular form in Table II. Both the currents (of Figure 8.1 and 8.5) are then compared to the waveform of Figure 8.8. Figure 8.8 shows the simulated transformer current. Also compared are the FFTs of the three waveforms. (Figure 8.2, 8.4 and 8.8).

Table. II

	Laboratory Test (Figure 8.5 and 8.7)	Simulation Results (Figure 8.8)	Field Data (Figure 8.1 and 8.2)
Peak Value of Current	30 Amps	29 Amps	27.82 Amps
RMS Value of Current	19.8 Amps	20.2 Amps	18.1 Amps
Crest Factor	1.515	1.435	1.537
THD	14.1	11.2	12.8

Holding the field-recorded data as reference the relative percent values of the laboratory and simulation results is shown below in Table III.

Table. III

	Laboratory Test (Figure 8.5 and 8.7)	Simulation Results (Figure 8.8)
<b>Peak Value of Current</b>	7.8%	4.24%
<b>RMS Value of Current</b>	9.39%	11.6%
<b>Crest Factor</b>	-1.43%	-6.636%
<b>THD</b>	10.15%	-12.5%

Looking at the waveforms figure 8.1 through figure 8.8 and Tables II & III, we note that the field recorded and the simulated current contain the domestic load current. The laboratory test waveform however is only the charger current. In the simulation the domestic load is taken as linear load (Figure 6.4) while in reality (Field recorded) the domestic loads may contain some non-linear loads. Thus the THD of the field current is higher than the THD of the simulated current. The laboratory test current consists of only the charger current.

## CHAPTER 9

### DERATING OF DISTRIBUTION TRANSFORMERS

#### 9.1 Method of Calculation

##### 9.1.1 ANSI/IEEE C 57.110 Method

The method used for calculating the derating of the distribution transformer is the ANSI/IEEE C 57.110 (see Section 2.3.1). Using the method described in Section 2.3.1, the derating has been calculated as a function of the current drawn by the charger. The derating curve is shown in Figure 9.1. In the calculations the derating is calculated taking the charger current as the base. So  $f_h$  in equation 2.1 is calculated dividing each harmonic component by the amplitude of the fundamental charger current. Thus, in this method the value of  $f_h$  for the fundamental component is always 1. This is the procedure employed by ANSI/IEEE C57.110 method. From the curve of Figure 9.1, we get the minimum and maximum limits of derating.

Table IV. Maximum and Minimum Derating Using ANSI/IEEE C57.110

Maximum Derating	20%
Minimum Derating	99.95%

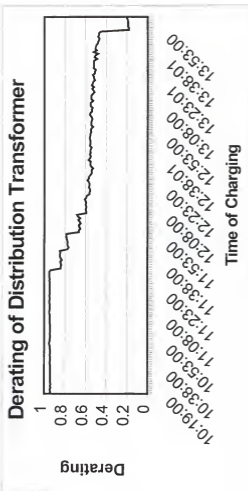


Figure 9.1. The Transformer Derating Curve for the Complete Charging Cycle

### 9.1.2 Modified ANSI/IEEE C 57.110 Method

The ANSI/IEEE C57.110 method calculates the derating of the transformer based on the charger fundamental current. In reality the transformer in a distribution system is supplying other loads. Also from figure 9.1 it can be seen that the transformer derating at 13:53 hours is as low as 20%. This calculation is done taking the charger fundamental as base, and from Figure 5.9 we see that the charger current at 13:53 hours is just about 5 Amperes. This would form only a small percentage of the total load on a distribution transformer of 37 KVA rating. Thus, although the derating based on C57.110 method is very high the effect of the small current on the transformer would be much less significant. In the modified ANSI/IEEE C57.110 method the calculation of transformer derating is done based on the maximum current carrying capacity of the transformer. Since the transformer derating should be a concern when the load on the transformer is full or close to full load this method calculates the derating based on full load current of the transformer. The derating of a 37 KVA transformer using the modified method is shown in Figure 9.2.

### 9.2. Transformer Derating with Fast Time Chargers

Based on the simulation results of section 6.4, the modified ANSI/IEEE C57.110 method has been used to calculate the derating of distribution transformers.

The derating has been calculated based on the 37 KVA distribution transformer whose specifications are given in Section 6.1.3. Figures 9.3 and 9.4 show the transformer derating for the two simulated load scenarios.

### 9.3. Conclusion

The derating of the distribution transformer based on ANSI/IEEE C57.110 method is significant but it does not consider the current carrying capacity of the transformer when calculating the derating. The modified approach calculates the derating of the transformer based on the full load current of the transformer. It is obvious that based on this method we see that the GM EV1 charger does not significantly derate the transformer. One thing that may be noted here is that the ANSI/IEEE C57.110 method is generally applied to find the derating of large power transformer and gives highly conservative results for distribution transformers. It is strongly recommended that the equation for derating of distribution transformers be experimentally determined with KVA ratings of concern to FPL. (See Chapter 10). The derating for the fast charging time chargers as seen from figures 9.3 and 9.4 is much higher. It is expected that the fast chargers will be more prevalent than slow chargers if consumer preference is not modified by the utility industry.

### Derating of Distribution transformer

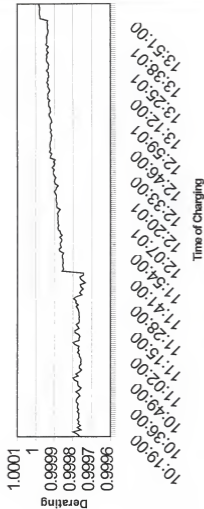
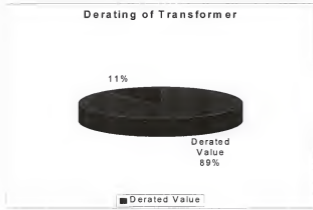
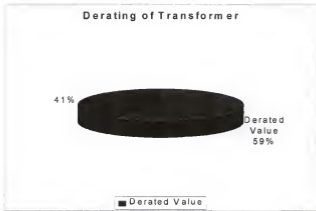


Figure 9.2. Transformer Derating using the Modified ANSI/IEEE Method



a.



b.

Figure 9.4. Derating Corresponding Short Charging Times a.) 1.2 Hours b.) 45 minutes

## CHAPTER 10 CONCLUSIONS

### 10.1. Summary and Conclusions.

The objectives of the project outlined in section 1.3 have been achieved. The behavior of four distribution nodes (FPL\_1 to FPL\_4) has been monitored. The load behavior with and without the EV load has been recorded. Volume II of the final report contains samples of the recorded data with an executive summary. By performing the laboratory test on the GMC EV1 charger charging a fully discharged battery, the charging characteristics of the charger has been determined. The charger takes about 3 hours to charge a nearly fully discharged (15% charge) battery to full (100%) charge. The harmonic spectrum of the transformer current charging the discharged battery has been determined. The snap shots of the current waveforms have been recorded and studied. Some of these waveforms have been included in this report. Based on the laboratory data a computer model of the charger and the distribution system has been developed. Comparing the simulation results to the laboratory results and the field data has validated the simulation results. The simulated currents are roughly 4 to 10% away from the field recorded currents, in their magnitude and distortion. Based on the field data, laboratory results and the simulation results the derating of the distribution transformer has been calculated. Based on the field data, laboratory results and the simulation results the derating of the distribution transformer has been calculated. The two methods suggested

for the calculation of derating have been presented and compared. The maximum and minimum limits of derating have been suggested. Using the first method the maximum derated value is 80% and the minimum value is 1%. Using the modified method the derating remains close to 99 % throughout the charging cycle. The transformer derating results corresponding to fast charging (45 minutes and 1.2 hours) chargers has been presented.

A Microsoft Excel based program has been provided to FPL. This program shall enable the user to find the derating of the transformer using the harmonic content information of the load on the transformer.

#### 10.2. Scope For Further Research

The transformer derating has been calculated using the IEEE /ANSI method. The formula is an empirical formula. To get a highly accurate measure of the derating of transformers, laboratory tests should be performed. These tests can be performed in the Power Laboratory in the Electrical and Computer Engineering Department at the University of Florida. Using the real time program R4™, the computer can generate low voltage controlled harmonic signals. These signals will be then amplified using the power amplifier in the laboratory and fed to the transformer under test. Temperature sensors placed selectively on and inside the transformers will sense the rise in the core and winding temperatures. The change in the temperature rise with a change in harmonic content from pure sinusoidal to very high harmonic content can be gauged. The transformers can be

tested for different harmonic scenarios and loads. Thus an exact formula for the derating of transformers can be evolved. As the harmonic generation can easily be controlled using the computer, affect of individual harmonics can also be studied. This information can be particularly useful to FPL for the design of harmonic filters that may need to be installed in places where the load is highly sensitive to harmonics. Also, at sites where the load is known to generate a significant amount of a particular harmonic, these tests can provide a strong basis for calculating the derating of equipment and thus the design of appropriate transformers.

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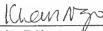
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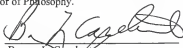
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